A New Method for the Quantitative Measurement of Localised Absolute Water Content using MRI

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INTRODUCTION

Localised quantitative determination of absolute water content plays an important role in the objective evaluation of disease states including brain oedema. Current methods employed for the detection of brain oedema relying on T_1- or T_2-weighted images are of limited use in the detection of global oedema because the resulting global change in signal intensity is hard to detect. These methods also fail if oedema is accompanied by other pathological conditions that result in a change of relaxation times. Even under these circumstances, determination of absolute water content may provide useful information as it is a direct measure of the local spin density. Published methods for water content mapping are frequently based on the mapping of T_1 or T_2, and the conversion of the measured relaxation time to absolute water content using either empirical relationships [1] or mathematical models [2]. They suffer from similar limitations as the T_1- and T_2-weighted sequences. The same applies for sequences that correlate the magnetisation transfer contrast (MTC) ratio to water content [3]. Spectroscopic sequences can provide accurate measures of water content, but spatial information is lost [4]. Several authors have published methods relating the relative spin density in an object to the spin density of pure water. Whilst not being limited by the factors described above, they either do not correct for B_1 inefficiencies [4], relaxation time related effects [5], temperature differences [6], provide only single slice information [7], determine the water reference by a independent scan [8] or require measurement times that are not suitable for clinical applications [9]. We present a method for the localised measurement of absolute water content based on the fast, multi-slice and multi-time-point T_1-mapping sequence TAPIR [10]. TAPIR provides a very efficient sampling of the T_1 relaxation curve which can be extrapolated to a inversion time TI=0 to extract the parameter M_0(object) that is directly proportional to the spin density ρ. An absolute measure of water content is obtained by placing a reference probe containing doped water within the FOV during the measurement thereby relating the parameter M_0(object) to M_0(reference). The method we present corrects for different temperatures of object and reference probe as well as for inefficiencies in the inversion pulse [11]. T_2^* decay differences between reference probe and object are corrected by a newly implemented sequence for T_2^* mapping. Incorporating all correction factors, the spatial water content in vivo can be determined with a speed and precision that matches clinical demands.

METHODS

T1 mapping using TAPIR was performed with the following parameters: TR=12.5ms; TE_1: TE_2: TE_3=2.8: 5.1: 7.5ms; α=18°; 12 slices; 20 time points; matrix size=128^2; FOV=220mm; slice thickness=4mm; sequential excitation; delay time τ=2s. The first point for the first slice on the recovery curve was sampled 10ms after inversion. The T_1-weighted images were fitted using an in-house tool based on the Levenberg-Marquardt algorithm to create a T_1 and an M_0 map [10]. Inefficiencies of the inversion pulse were determined and corrected using the procedure described in [11]. The T_2^* relaxation time was determined by the sequence shown in Figure 1. Following a slice selective alpha pulse, the signal is phase encoded by the application of a gradient to encode for the acquisition of the outermost k-space line. By the application of a gradient train with alternating polarity in the readout direction, the signal is repeated read during T_2^* relaxation with an echo separation of 2ms. Following readout, the residual transverse magnetisation is spoiled by the application of crusher gradients in all three directions. This procedure is then repeated until the highest frequency line for all slices has been acquired; the procedure is repeated for all subsequent lines of k-space. A T_2^* map was obtained by a χ^2-fit of the resulting T_2^*-weighted images using MRVision Version 1.6.5a (MRVision Co., Winchester/USA). The measurement parameters for the T_2^* mapping sequence were: TR=150ms; TE=4ms; α=90°; 12 slices; 64 time points; Δ=2ms; matrix size=128^2; FOV=220mm; slice thickness=4mm; rf-spoiling employed; 10 preparation scans. Phantom measurements were performed using tubes with different mixtures of water (H_2O) and heavy water (D_2O) with volume ratios VR=V(H_2O)/(V(D_2O)+V(H_2O)) between 50% and 99% doped with small amounts of $MnSO_4$ between 0.373mM/L and 0.411mM/L. As D_2O is not MR-visible at the proton frequency, it does not contribute to the observed signal. For the in vivo measurements, a reference probe containing doped water was placed in the FOV during image acquisition. The total measurement time for T_1 mapping, T_2^* mapping, and the inversion efficiency measurement was approximately 15 minutes. The temperature of the reference probe was determined immediately before and after the measurement and M_0 (reference) was extrapolated from the mean temperature to a body temperature of 37°C by a relation given in [8]. The absolute localised water content W_{MR} after correction is then given by:

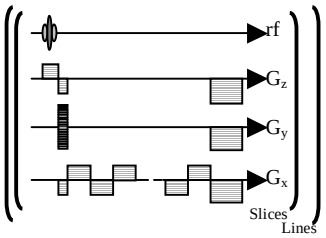

Figure 1: Schematic representation of the T_2^* mapping sequence.

$$W_{MR} = \frac{M_0(\mathrm{ROI}) \cdot e^{\frac{TE_2}{T_2^*(ROI)}}}{M_0(\mathrm{reference},\ \mathrm{T} = 37°\mathrm{C}) \cdot e^{\frac{TE_2}{T_2^*(reference)}}} \ .$$

RESULTS AND DISCUSSION

Fig. 2a shows the relation between water content W_{MR} measured by MR and the H_2O volume ratio VR. A highly linear correlation between W_{MR} and VR is observed (Pearson correlation coefficient r=0.9967). The absolute standard deviation of W_{MR} lies between 1.9 and 2.5% and is independent of W_{MR}. In Fig. 2b the water map from a multi-compartment phantom is shown where the compartments contain different volume ratios of H_2O. Representative results from a 23 year old healthy volunteer are shown in Fig. 2c. The water content in the ROI selected from white matter is (75.1±0.9)% compared to (80.9±1.1)% from grey matter. These results clearly demonstrate that quantitative mapping of water content in vivo is feasible with high precision in clinically-relevant measurement times. A study, involving a large group of normal healthy volunteers, is currently underway to measure quantitatively the relationship between water content and age in the human brain.

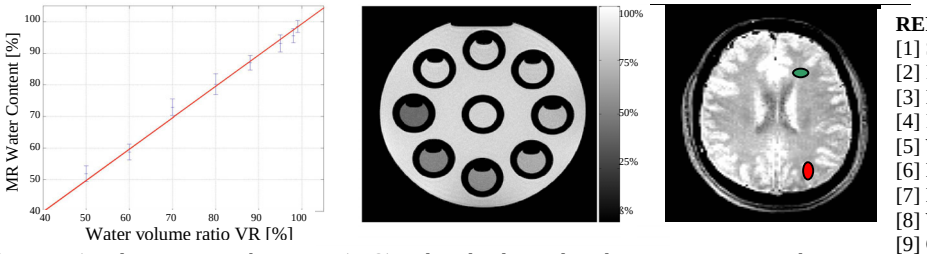

Figure 2: a) Volume ratio VR between V(H_2O) and total volume plotted against MR measured water content. b) Example of a water map from a phantom. c) In vivo water map. The red area shows a selected ROI in grey matter, the green area an ROI in white matter.

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